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Energetic additives offer the possibility of increased performance of rocket engines. For hydrocarbon-fueled rocket engines, however, increased performance tends to be associated with increased severity of combustion instability. An exploration of the role of fuel and flame chemistry on combustion instabilities in liquid rocket engines is presented, with the goal of determining whether changes in the fuel energy content and flame speed can improve combustion stability. A limited set of experiments, analyses, and computations were conducted. In summary, it was determined that JP-8 and ethanol drops loaded with nano-Al additives burned differently. An exploratory computational study using Large Eddy Simulation indicated that faster-burning fuels actually increased stability. Experiments in a model rocket combustor indicated that there are coupled effects including injector flow dynamics and chemistry.

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Effects of Energetic Additives on Combustion Dynamics

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Introduction

Energetic additives offer the possibility of increased performance of rocket engines. For hydrocarbon-fueled rocket engines, however, increased performance tends to be associated with increased severity of combustion instability. A number of questions exist before energetic additives can be used successfully in rocket engines, for example:

- Why do combustion stability and performance tend to oppose each other in hydrocarbon-fueled rocket engines? In H_2–fueled engines performance and stability increase together.
- Can an increased rate of energy release be used to stabilize combustion, and increase performance for hydrocarbon-fueled engines?
- How can the coupled physical and chemical processes of injection and combustion be used to enhance stability?
- If the 'steady' combustion rate is sufficiently high, can effects of flow perturbations be reduced?
- Can particles be used to provide acoustic damping?

The work described here is an initial, exploratory investigation into the role of fuel and flame chemistry on combustion instabilities in liquid rocket engines. The goal of the work is to determine whether changes in the energy content of the fuel can improve combustion stability. A limited series of experiments, analyses, and computations were conducted. In summary, it was determined that the effects of nano-Al additives on combustion instability JP-8 and ethanol drops loaded with nano-Al additives burned differently, and had different stability results in model rocket combustor. An exploratory computational study using Large Eddy Simulation indicated that faster-burning fuels actually increased stability. Experiments in the CVRC indicated that there are coupled effects including injector flow dynamics and chemistry.

Results

The preliminary study proceeded along two primary fronts. First, a Continuously Variable Resonance Chamber (CVRC) was used as a tool to explore effects of fuel type and energetic additives on the limit cycle amplitudes of longitudinal instabilities. Second, an investigation of the effects of adding nano-aluminum (n-Al) on processing and static fluid mechanics, and drop burning studies, was done. A very limited investigation into the effects of chemical kinetics on eombustion instability was also performed. The results from these studies are deseribed in more detail below.

Tests in a Continuously Variable Resonance Combustor. Thc CVRC shown in Fig. 1 has been used to measure the limit cycle combustion instabilities with methane fuels.[1] Tests at fixed geometry eonditions have also been used to determine the limit eyele amplitudes with JP-8 fuels.[2] Thus this device provides an exeellent vehiele with which to examine thc effeets of additives on combustion instability.

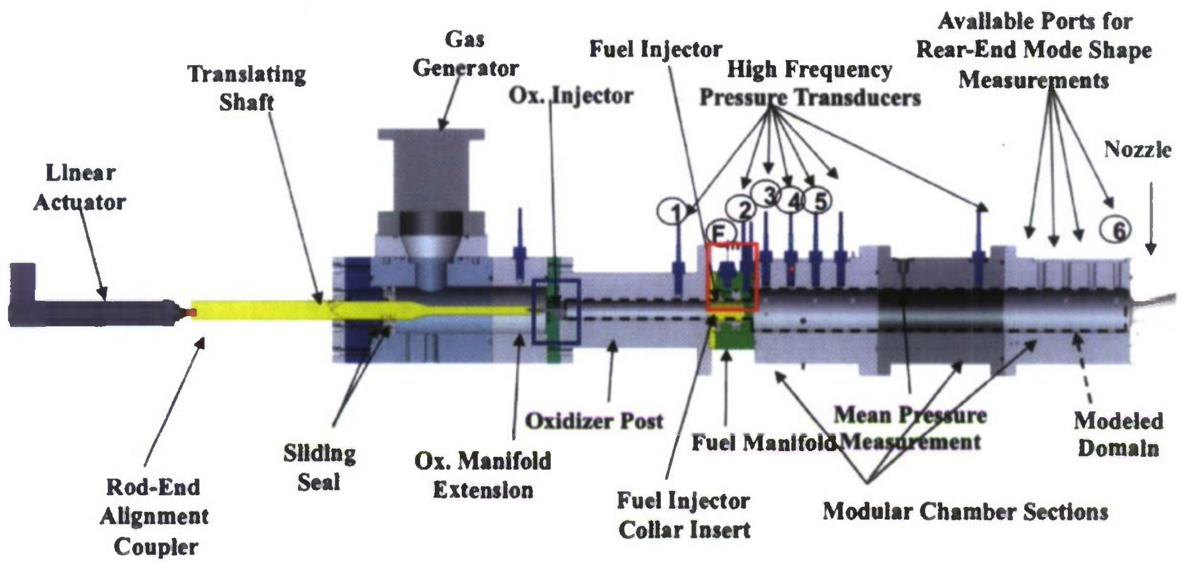


Fig. 1. Continuously Variable Resonance Chamber. Location of choked oxidizer inlet is translated by cleetro-mechanically actuated shaft. Oxidizcr tube length varies from 7.5- to 3.5-in, representing traverse from half-wave resonator to quarter-wave resonator. Chamber length is 15-in.

To test the JP-8 and ethanol fuels loaded with n-Al, the CVRC was operated in a fixed gcometry eondition. In tests that evaluated the effeets of hydrogcn content in methane fucl, the CVRC was operated with a traversing oxidizer inlet. In these latter tests, the oxidizer post length was started at 7.5-in, and moved to 3.75-in, representing a half-wavc and quarter-wave resonator, respectively, for the 15-in long combustor. In both types of tests, high frequency pressure eontcnt was measured at the loeations indieated in Fig. 1. Figure 2 shows a typical system pressure-time trace during the test.

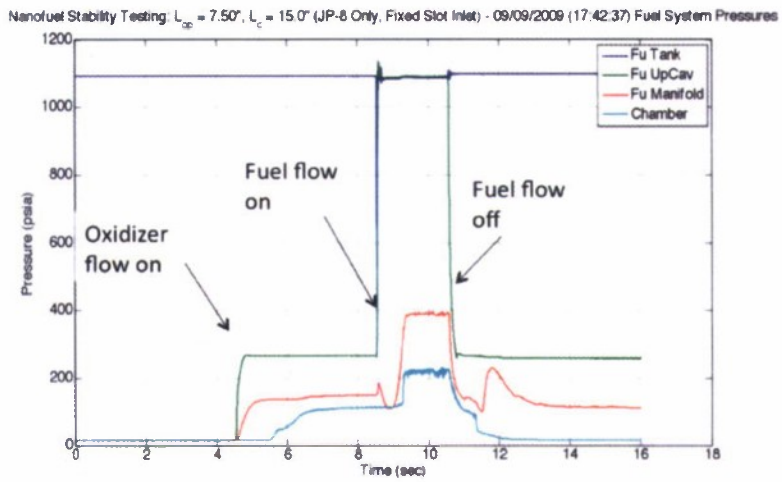


Fig. 2. Time trace of system-level pressures during a typical test.

The high-frequency pressure data were analyzed for spectral content. Figure 3 shows the power spectral density of a test using JP-8 fuel loaded with n-Al. It can be seen that the n-Al has essentially no effect at this particular condition.

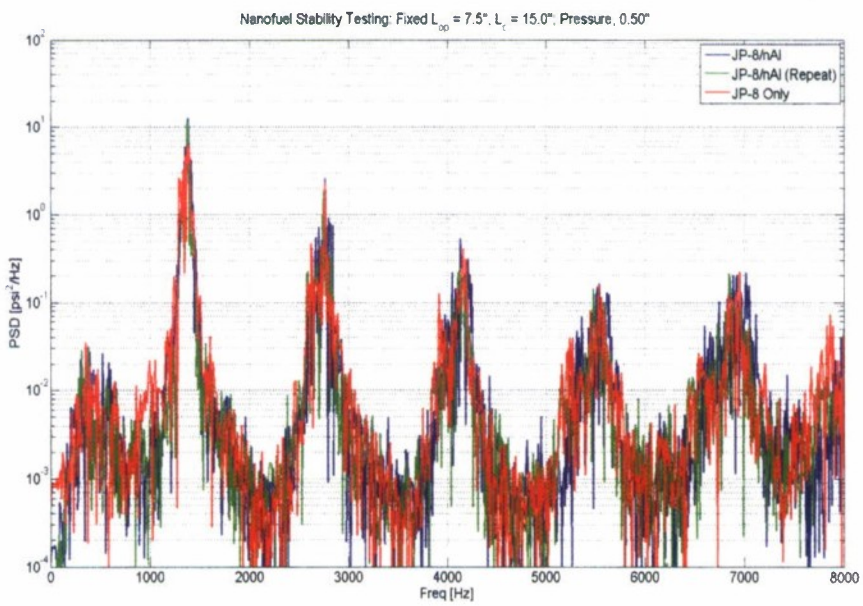


Fig. 3. Power spectral density of instability using JP-8 fuel loaded with 1% by weight of n-Al. Post length is fixed at 7.5-in. Essentially no difference can be measured.

In contrast, it was observed that 1% by weight of n-Al in ethanol did have an effect. Figure 4 shows the power spectral density of a longitudinal instability in this case. It is seen that the presence of n-Al leads to slightly high noise levels, and increases the frequency of the instability slightly. An analysis of this effect was not done, but we assume it is due to a difference in sound speed.

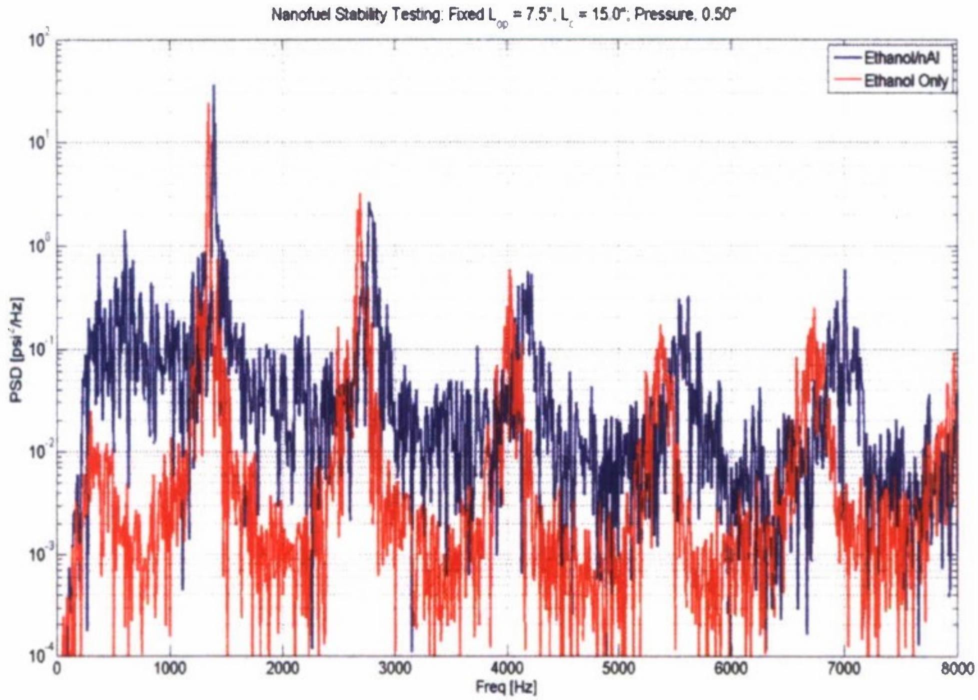


Fig. 4. Power spectral density of instability using ethanol fuel loaded with 1% by weight of n-Al. Post length is fixed at 7.5-in. Presence of n-Al increases noise level slightly and tends to increase the frequency of the instability.

Results with the n-Al additives were fairly unremarkable. To investigate the effects of energetic additives more systematically, CVRC tests turned to measuring the effects of hydrogen addition on combustion instability. It is known from other experiences (e.g., Ref 3) that the addition of hydrogen tends to dampen combustion dynamics in gas turbine combustors. It is also widely known that hydrogen-fueled rocket engines are generally more stable than hydrocarbon-fueled engines. If the effects of hydrogen addition on combustion stability in rocket engines could be determined, then energetic additives could presumably be designed that would provide both an increase in performance and increased stability margin.

To evaluate the effects of hydrogen, weight percentages of 0, 5, 10, and 15% hydrogen were added to methane. The CVRC was operated in the translating mode. Table 1 summarizes the test conditions.

Table 1. Test Condition Summary for Hydrogen Addition into Methane Fuel

H_2 Concentration	0%wt	5%wt	10%wt	15%wt
Pc [psia]	202	202	195	200
Ox. Mass Flowrate [lb_m/s]	0.72	0.71	0.700	0.697
CH_4 Mass Flowrate [lb_m/s]	0.105	0.092	0.084	0.076
H2 Mass Flowrate [lb_m/s]	0.000	0.0046	0.0084	0.0116
Equivalence Ratio	1.169	1.156	1.166	1.163

Representative power spectral density plots for the high-frequency pressure measured 0.5-in downstream of the injector face are shown in Fig. 5. The circled areas corresponding to the maximum amplitude of the first longitudinal mode were used to comparison the relative stability between the various hydrogen percentage cases, as shown in Fig. 6.

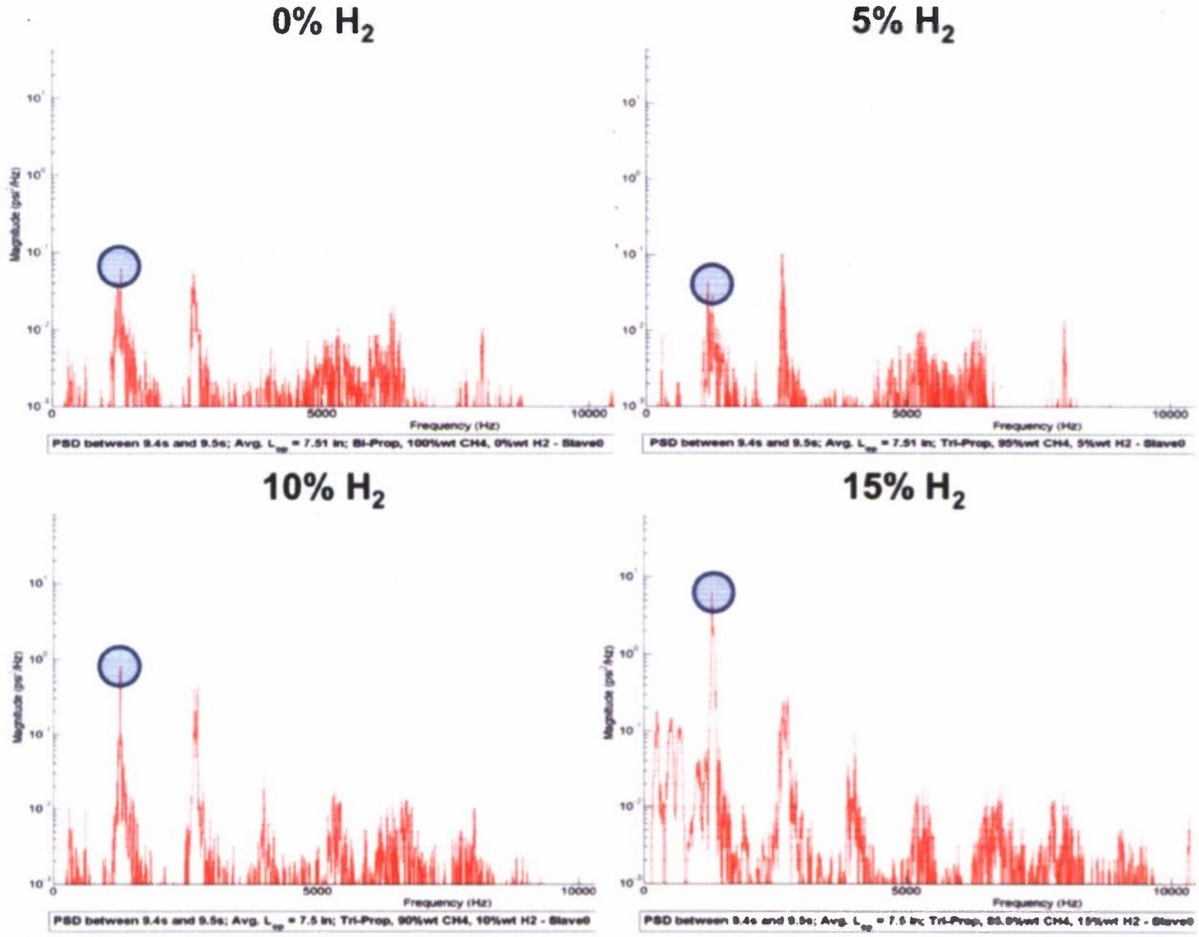


Fig. 5. Representative power spectral density plots for tests indicated in Table 1. Measurements are made at 0.5-in downstream of the injector face. Injector post length is 7.5-in. Circled areas correspond to maximum amplitude of first longitudinal mode.

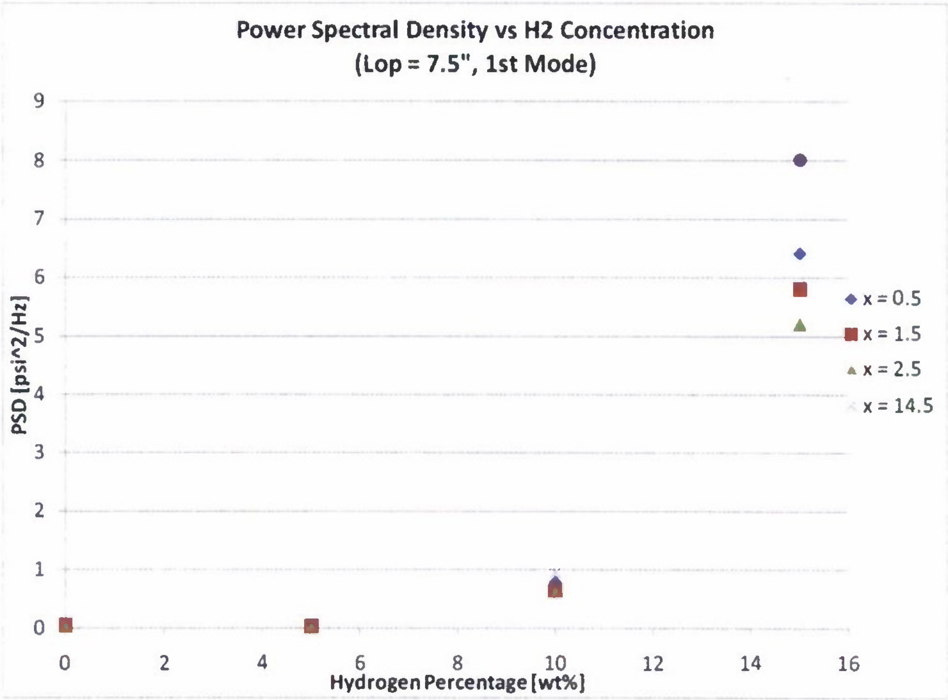


Fig. 6. Relative comparison between hydrogen percentage cases on amplitude of first longitudinal instability. Oxidizer post length is 7.5-in. Measurements are shown for four different locations with respect to the injector face.

Similar analysis was done for oxidizer post lengths of 4.5-, 5.5-, and 6.5-in. A summary of all these cases is shown in Fig. 7.

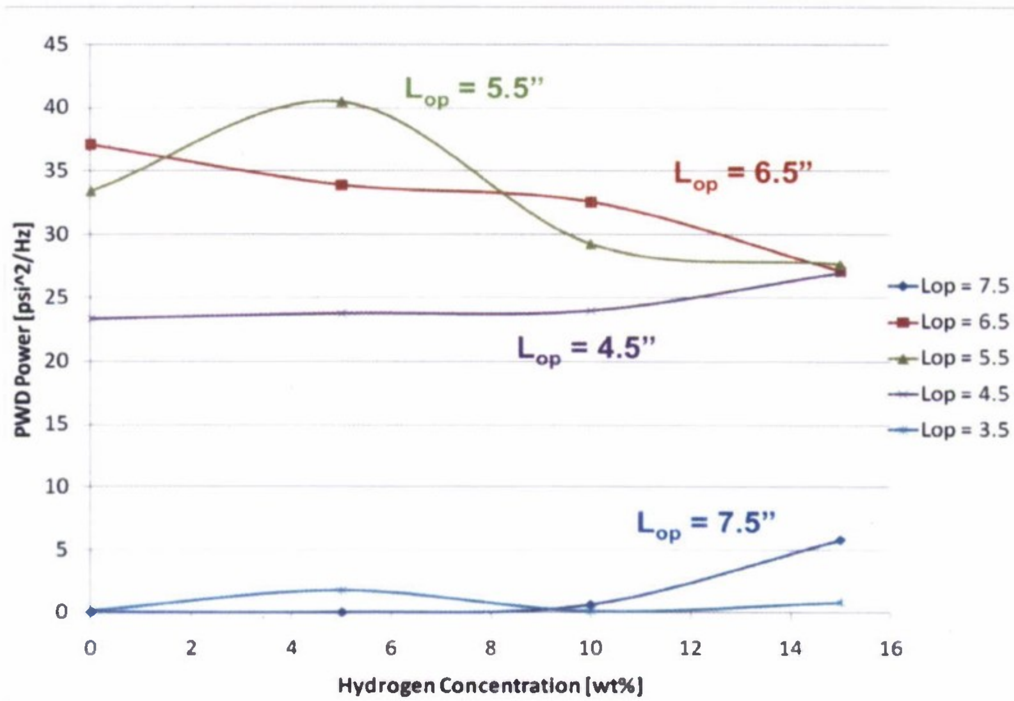


Fig. 7. Summary plot showing effect of hydrogen concentration on amplitude of first longitudinal mode instability for varying oxidizer post length.

Computational Study. Results from a brief computational study of the effects of reaction rate on combustion instability are shown in Figs. 8 and 9. Figure 8 shows the computed pressure-time trace for a case during the limit cycle using realistic reaction rates (shown in blue) and the case where the reaction rate was arbitrarily increased by a factor of 10^4. Fig. 9 shows the computed reacting flowfield for these two comparison cases.

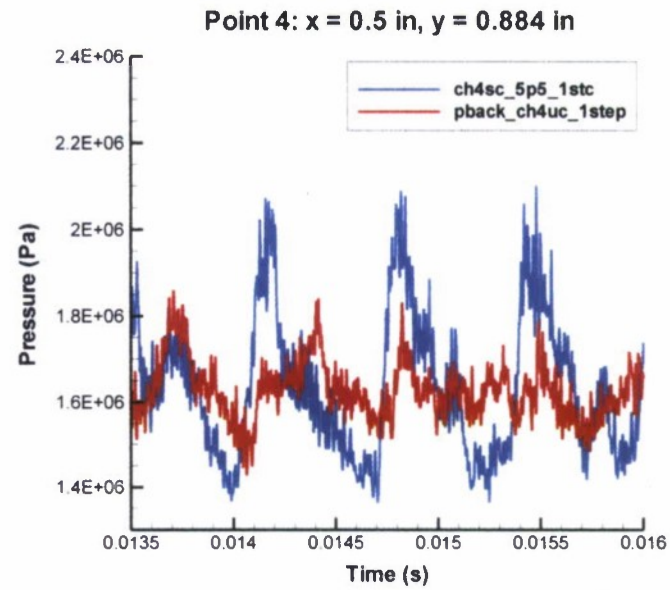


Fig. 8. Pressure-time trace for realistic kinetics (blue trace) and fast kinetics (red trace).

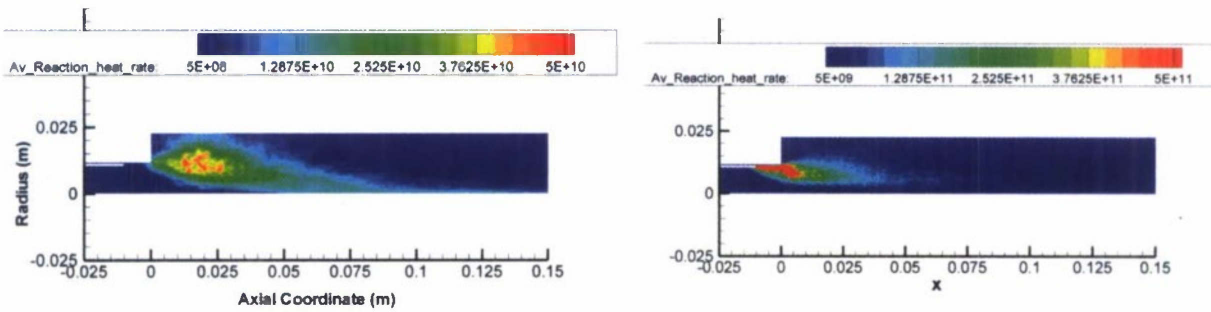


Fig. 9. Effects of reaction rate. The configuration shown in Fig. 1 was used, and reaction rate was changed arbitrarily by pre-multiplying the pre-exponential coefficient by 10^4.

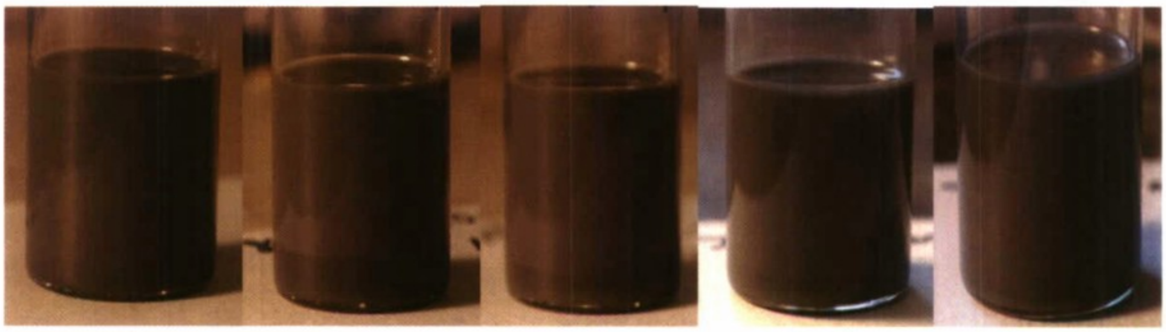
Mixing Results

There were two methods used to try to suspend the nano-particles in fuels. These included using an ultrasonic horn and a resonant mixer. The ultrasonic horn mixed the particles by introducing localized sonic waves to provide for vigorous mixing around the tip of the horn. Fuels were mixed for 30 seconds at 50% power at several second durations and then checked to see if particles were dispersed. If they were not, this process was repeated until particles were fully dispersed. This method provided for some heating of the fuel while mixing causing some evaporation of the fuel. The other method used a Resodyn LabRam mixer that finds the resonant frequency of the system and then apply a vertical cyclic force at that frequency causing vigorous movement of the particles in the suspension finally dispersing them. These mixtures were typically mixed for 30 seconds at various intensities and then checked for complete dispersion and repeated until desired results were achieved. This method did not add very much heating during the mixing process. Through visual observations, there did not seem to be much of a difference between the two mixing types on the final outcome of the mixed fuel.

Four fuels were used to suspend the nano-particles. These included isopropyl alcohol, ethanol, hexane and JP-8. Two surfactants were used making up 3% by weight of the total mixture: Neodol and Tergitol. Various types of nanoscale aluminum were used as well that consisted of different sizes of aluminum with different coatings including palmitic acid and a paraffin. The nano aluminum was always 1% by weight of the total mixture. The time that these solutions remained suspended almost never exceeded 30 minutes. Most suspensions started to precipitate nano-particles in less than 15 minutes after mixing. A summary of these results can be found in Table 2. The results reported in this table were all from fuels that were mixed using the sonic horn. An example of the observations made of settling is shown in Fig. 10.

Table 2. Time for different fuel mixtures to precipitate nano Aluminum.

Fuels	50 nm L-Alex	100 nm L-Alex	Novacentrix (80 or 50 nm)	Coated in Palmitic Acid	Coated in Parafin	3% Neodol	3% Tergitol	Time (min)
Isopropyl	*			*				<10
Alcohol	*			*		*		<0
		*		*	*			<30
		*		*	*	*		<0
		*		*	*		*	<30
		*						<16
		*					*	<5
	*	*	*					<9
JP8	*			*				<11
	*			*		*		<0
		*		*	*			<0
		*		*	*	*		<0
		*		*	*		*	<14
	*	*	*					<3
		*						<7
		*					*	<6
	*	*				*		<0
			*			*		<11
Hexane	*	*				*		>30
			*			*		<0
	*	*	*					<0



Initial 11 min. 37 min. 1 hr. 18 min. 4 hr. 11 min.

Fig. 10. Still pictures of 1% by weight 80 or 50 nm Aluminum with 3% by weight in JP-8 after mixing with and ultrasonic horn.

Droplet Combustion

Qualitative observations were made of several types of nano-fuels burning. These fuel mixtures included JP-8 with 3% by weight Neodol and 1% by weight of 80 nm Novacentrix nano Aluminum while the other fuel consisted of 190 proof ethanol and 1% by weight 80 nm Novacentrix nano Aluminum. Both of these fuels were mixed using the Resodyn mixer as described above. These droplets were burned on steel syringes that allows some heat transfer that probably affected burning rate of the droplet. For this purpose, only qualitative observations are noted. Future work will use small fibers to suspend the droplets.

The JP-8 mixture behaved qualitatively very differently than the ethanol mixture. The aluminum did not appear to react significantly during the combustion of the actual liquid fuel. This was concluded due to the lack of bright flashes that are typically observed in the combustion of aluminum. Most of the aluminum reacted in the final moments of the droplet life causing a large "explosion" of aluminum combustion that can be seen in Fig. 11. The ethanol mixture on the other hand exhibited aluminum reacting throughout most of the lifetime of the droplet with an increase towards the end of the droplets life. This difference in combustion process at atmospheric conditions would indicate that the combustion process within the rocket combustor may not be the same either for different fuels.

There are several reasons why these fuel mixtures could burn differently. The JP-8 mixture required a surfactant that suspends the aluminum in the JP-8. The ethanol mixture did not have a surfactant but suspended the nano-particles by itself because it is polar. The volatility of the fuels is expected to be different (ethanol would have a higher volatility than JP-8). This could allow the aluminum to be entrained into the gas easier and react throughout more of the life of the droplet. More work is needed to determine if this or other causes explain these observations.

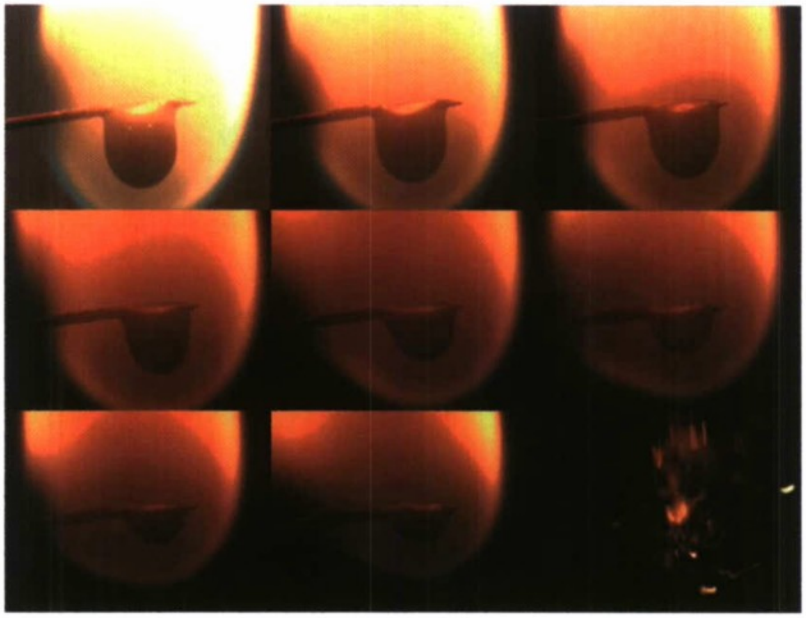


Fig.11. Combustion process of 3% by weight Neodol, 1% by weight 80 nm aluminum and JP-8.

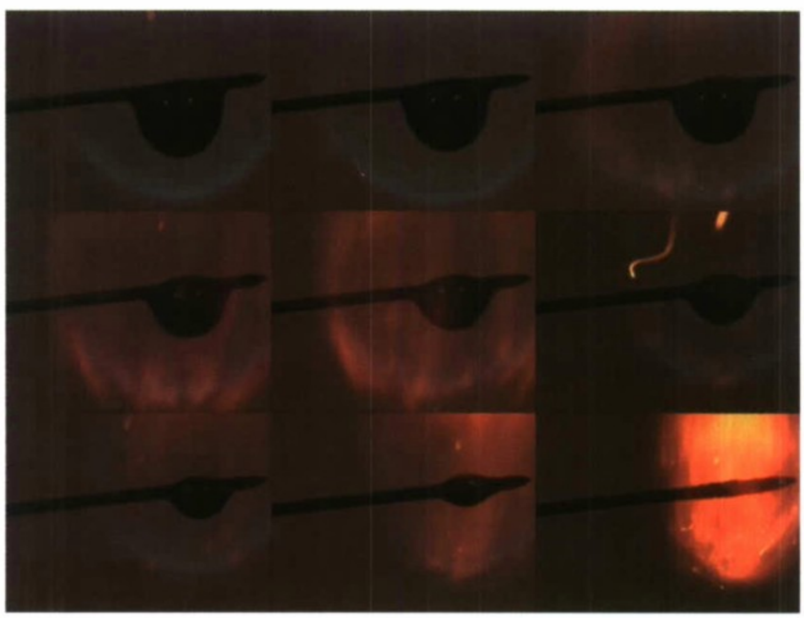


Fig. 12. Combustion process of 1% by weight 80 nm aluminum and 190 proof ethanol.

Conclusions

In summary, the addition of 1% n-Al had little effect on JP-8 stability, whereas the addition of 1% n-Al seemed to be slightly destabilizing with ethanol. The addition of H_2 to methane indicated combined fluid mechanic and chemistry effects, requiring a more systematic study involving experiment, analysis, and computation to determine how an energetic material should be added to achieve simultaneous improvements in stability and performance. Suspension properties of nano aluminum in two fuels have been examined and qualitative combustion observations have been observed.

From the results obtained here, it is clear that further studies are needed to fully understand effects of nanofuels and hydrogen addition on performance and combustion instabilities. With regards to hydrogen addition, we need to seek answers to the following questions:

- Can increased burning rates of hydrocarbon fuels be used to stabilize combustion?
- What is the detailed mechanism of combustion instability in ORSC combustors? Can it be captured in a reduced order combustion response model?
- Why is the effect of hydrogen addition on stability geometry-dependent (e.g., fluid dynamics and acoustic flow field)
- Can a practical hydrogen carrier be developed for use as an additive to hydrocarbon fuels?

With regards to additives such as n-Al, the following questions remain:

- One additive configuration resulted in decreased stability – what about other mass concentrations and particle sizes? What causes the increased instability?
- Could alumina produce a catalytic effect? What about other types of nano particles?
- Significant effects on ignition for both JP8 and ethanol have been noted– is ignition behavior related to effects on combustion stability?
- Do nano particles influence atomization and vaporization?
- Do nano particles provide acoustic damping? To what degree?